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The Influence of Prescribed Fire on Fine Particulate Matter Pollution in the Southeastern United States

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Key Points:
- Burn permit records show an association between prescribed fire and air pollution recorded at monitoring sites in the Southeast United States
- Fire permits can explain more than 25% of the variability in observed $PM_{2.5}$ concentration, and prescribed fire influence can persist for over a day
- At most sites, the association between air quality and permitted burning is stronger than the association with satellite-derived burn area

Supporting Information:
- Supporting Information S1

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Abstract Prescribed fire is the largest source of fine particulate matter emissions in the Southeastern United States, yet its air quality impacts remain highly uncertain. Here, we assess the influence of prescribed fire on observed pollutant concentrations in the region using a unique fire data set compiled from multiyear digital burn permit records. There is a significant association between prescribed fire activity and concentrations recorded at Southeastern monitoring sites, with permitted burning explaining as much as 50% variability in daily $PM_{2.5}$ concentrations. This relationship varies spatially and temporally across the region and as a function of burn type. At most locations, the association between $PM_{2.5}$ concentration and permitted burning is stronger than that with satellite-derived burn area or meteorological drivers of air quality. These results highlight the value of bottom-up data in evaluating the contribution of prescribed fire to regional air pollution and reveal a need to develop more complete burn records.

Plain Language Summary Prescribed fires, planned and intentionally ignited wildland fires, are frequently used in the Southeastern United States for different land management purposes, such as reducing the risk of catastrophic wildfires and restoring ecosystems. They are also the largest source of fine particle emissions into the atmosphere in the Southeast. However, the extent to which prescribed fires contribute to air pollution in the region remains unclear. In this study, data gathered from state burn permit records and regulatory air quality monitors are used to show that prescribe fire has an important influence on air pollution at multiple Southeastern locations. Additionally, our analysis suggests that burning permits can be more informative than satellite-derived fire data when evaluating the impacts of prescribed fire on regional air quality. These results reveal a need to improve available records of prescribed fire activity in order to better understand its full effect on air pollution in the Southeast.

1. Introduction

Wildland fires, including wildfires and prescribed fires, are the largest source of fine particulate matter ($PM_{2.5}$) emissions in the United States (U.S. EPA, 2018). Nationally, over 10 million Americans have been estimated to experience unhealthy $PM_{2.5}$ levels caused by wildland fires at least 10 days per year (Rappold et al., 2017), and fires are believed to contribute over 10% of the country's mean $PM_{2.5}$ concentration (Wilkins et al., 2018). Annual premature deaths and illnesses associated with short- and long-term exposure to fire smoke have been valued at more than $100 billion (Fann et al., 2018). Although wildfires attract considerable attention, much of the wildland fires in the United States are prescribed, representing more than 40% of the total reported area burned (NIFC, 2018).

Prescribed burning is the controlled application of fire to accomplish different land management objectives, including hazardous wildfire mitigation, and it can play a critical role in sustaining healthy ecosystems (Kobziar et al., 2015). In the United States, most of this burning (~70%) occurs in the Southeast (Chiodi et al., 2018), where it accounts for nearly 25% of primary $PM_{2.5}$ emissions (U.S. EPA, 2018). The Southeast also includes one of the largest urban-wildland interfaces in the country, with millions living in areas that neighbor or intermix with fire-prone land (Martinuzzi et al., 2015; Radeloff et al., 2018). These circumstances, combined with the propensity to conduct prescribed burns under conditions conducive to incomplete combustion, can lead to air quality and public health concerns in nearby communities (Haikerwal et al., 2015; Pearce et al., 2012; Price et al., 2016). However, fire is a natural feature of many Southern landscapes, where ecosystems may depend on its occurrence, and suppression has proven unsustainable (North et al., 2015; Williamson et al., 2016). Further, the air quality impacts of wildfires can far exceed those of prescribed burning (Zhao et al., 2019). A clear understanding of the effects of prescribed fire on air pollution is needed to develop mitigation strategies that jointly consider land management and public health goals.

Despite their significance, prescribed fire remains one of the most inadequately characterized major emission sources, and few studies have quantified its effects on air quality (Navarro et al., 2018). Several have relied on ambient measurements (e.g., X. Liu et al., 2017; May et al., 2014; Sullivan et al., 2014), statistical approaches (e.g., Balachandran et al., 2017; Z. Liu et al., 2016), or models (e.g., Garcia-Menendez et al., 2013, 2014; Y. Hu et al., 2008; Liu et al., 2009) to estimate the impacts of individual fire projects or the influence of burning at specific receptors. A smaller number of studies have attempted to quantify the impacts of prescribed fire at regional scales. Using chemical transport modeling, Ravi et al. (2019) found that prescribed fires can significantly affect regional air quality over areas of the Pacific Northwest. In the Southeast, some studies have modeled the regional impacts of burning on air quality (Tian et al., 2008; Zeng et al., 2008, 2016). However, these were based on the VISTAS inventory, which was compiled in 2002 and later shown to be incomplete (Zeng et al., 2016). More recently, Gaither et al. (2019) and Huang et al. (2019) used burning permits and a data fusion method to estimate smoke impacts in Georgia. Still, the influence of prescribed fire on air pollution over the Southeast remains uncertain.

Assessing the role of prescribed fire on U.S. air quality has been hindered by challenges associated with compiling fire data. Satellite-based products, used extensively in wildland fire smoke analyses, have proven incapable of detecting a large fraction of low-intensity, short-lived prescribed burns (Randerson et al., 2012). Over the Southeast, remote sensing fire data techniques are prone to large uncertainties in fire location, size, and timing (X. Hu et al., 2016; Huang et al., 2018; Nowell et al., 2018). Additionally, satellite-based detections do not discern between prescribed fires and other forms of biomass burning, including wildfires. In contrast, bottom-up fire inventories, such as burn permit records collected by state agencies and land managers, can include a larger number of fires and additional information. However, permits normally lack post-burn information and are susceptible to uncertainties due to inconsistencies in recordkeeping and data reporting requirements across agencies. Nevertheless, digital prescribed fire records maintained by several states have increased substantially in recent years.

In this study, we assess the influence of prescribed fire on observed $PM_{2.5}$ concentrations in the Southeastern United States based on permitted burning. Our analysis focuses on the states of Georgia and Florida, which include some of the most active burning areas in the United States (Melvin, 2018). These states also have two of the most complete digital permits inventories and have been estimated to include some of the largest health impacts attributed to fire smoke (Fann et al., 2018). We examine several types of prescribed fires and investigate how associations between prescribed burning and $PM_{2.5}$ vary spatially and temporally. Additionally, we compare these to associations with satellite-derived fire data and meteorological drivers of air quality.

2. Data and Methods

Georgia and Florida burning permits from 2013 to 2016 were compiled as an indicator of prescribed fire activity. In Georgia, burning permits are issued by the Georgia Forestry Commission (GFC). The GFC's digital records include burn area, date, type, and address. Most GFC permits do not include geographic coordinates, and the level of detail in recorded addresses varies widely. A geocoding algorithm was developed to match address data to a geographic location. Details about the geocoding algorithm used are described in the supporting information (Figure S1). Burn permits in Florida are authorized and collected by the Florida Forest Service (FFS). Digital FFS records list burn area, date, type, and coordinates. Only burns specifically labeled by the GFC and FFS as prescribed fires are considered in our analyses. These include silvicultural (intended for management, restoration, and care of forests and woodlands), land clearing (clearing of vegetation for development), and agricultural (associated with cultivation, pastures, or rangeland) burns in both states. The FFS additionally records the number and dimensions of pile burns (gathered vegetative debris). Other types of permitted open burns (e.g., recreational purposes, reduction of leaves on-premises, and structure burns) are not considered.

In our analysis of satellite-derived fire activity, we use 2015–2016 burn areas generated by the National Oceanic and Atmospheric Administration's (NOAA) Blended Polar Geo Biomass Burning EmissionsProduct (Blended-BBEP) (Zhang et al., 2011). The Blended-BBEP combines detections

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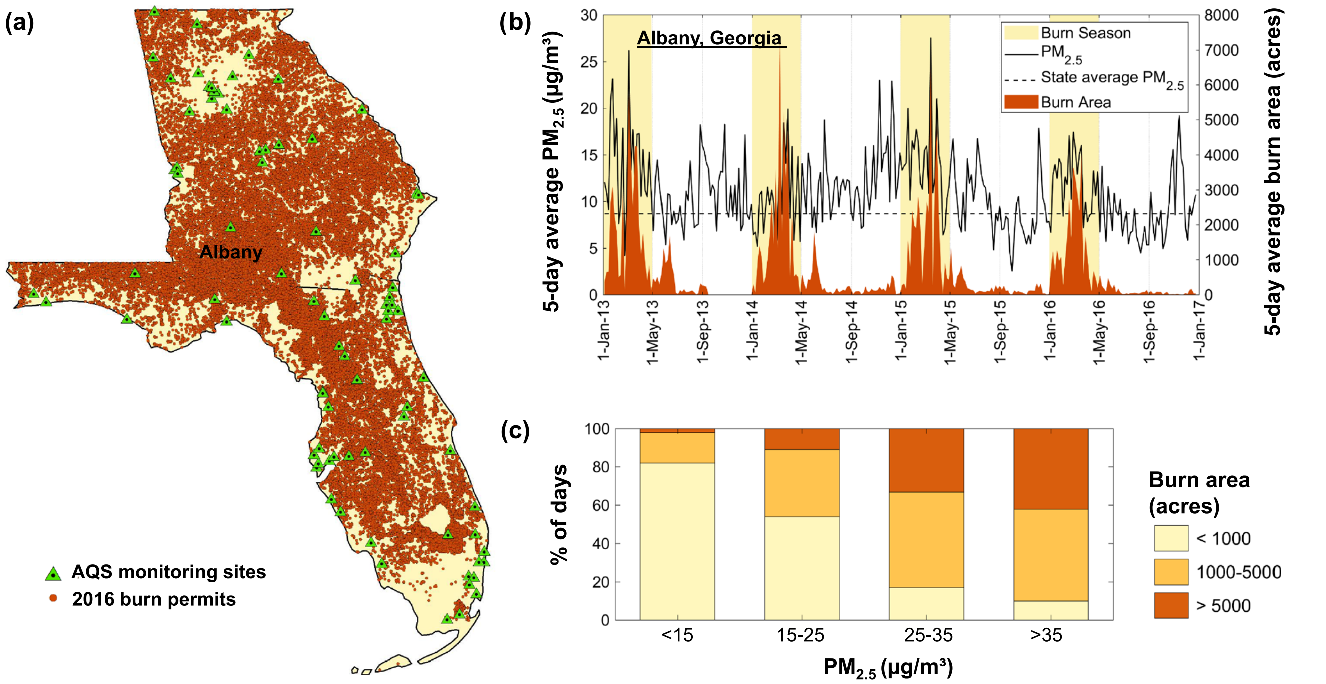

Figure 1. Prescribed fire in the Southeastern United States. (a) Spatial distribution of 2016 burn permits and AQS sites over Georgia and Florida. (b) 5-day average 24-hr $PM_{2.5}$ concentration at Albany, Georgia, and 5-day average daily acres burned within 60 km of the station. Georgia-average concentration (2013–2016) and burning season are also shown. (c) Relative percentage of days at all monitoring sites considered associated with varying air quality and burning levels during 2013–2016 burning seasons. Observations are 24-hr $PM_{2.5}$ concentrations, and burn areas are permitted acres within 60 km of the sites on the day of the observation and previous day.

from NOAA's Geostationary Operational Environmental satellites (GOES-East and GOES-West), the Moderate Resolution Imaging Spectroradiometer on the National Aeronautics and Space Administration's Terra and Aqua satellites, and the Advanced Very High Resolution Radiometer on NOAA's polar-orbiting satellites. We aggregate hourly Blended-BBEP fire detections into daily burn areas. Surface $PM_{2.5}$ observations are collected from monitoring sites included in the U.S. Environmental Protection Agency's Air Quality System (AQS) (U.S. EPA, 2012). We consider 24-hr average $PM_{2.5}$ concentrations available from all monitors in Georgia (31) and Florida (49) during the study period (Figure 1a). To examine the influence of meteorology on $PM_{2.5}$, we rely on weather observations recorded by the Automated Surface Observing System Network (ASOS), which includes 84 stations in Georgia and 97 in Florida (ASOS, 2000). Each air quality monitor is matched with the closest weather station available, up to 20 km away, allowing daily-average meteorology near the site to be estimated for approximately 90% of monitors.

The strength of the relationship between prescribed fire and $PM_{2.5}$ is assessed at all observational sites considered by estimating the bivariate correlation (Pearson correlation coefficient, PCC) between measured concentrations and permitted burn area near each site. Burning activity near each site is weighed by identifying fires and area burned (permitted or satellite derived) within a specified radius from the site and time period. Correlations between $PM_{2.5}$ and fire activity at varying radii (up to 60 km) from the monitoring sites are compared to evaluate how the influence of prescribed fire on air quality changes with distance. Beyond 60 km, the radius at most sites exceeds the coastal or state boundaries to which permits are constrained. Additionally, $PM_{2.5}$ concentrations are correlated with permitted burns recorded during varying periods of time, extending from the day of the observation to 3 days prior, to assess the duration of the fires' impact on local air quality. The analyses focus on the Southeastern burning season, extending from January to April, which concentrates most of the region's burning (Huang et al., 2018) and during which substantially stronger associations were identified compared to the rest of the year.

In addition, we use multiple regression to account for different types of burns in weighing the associations between fire activity and $PM_{2.5}$. Stepwise regression is used to create a generalized linear model at each monitoring site with 24-hr $PM_{2.5}$ concentration as the response variable and surrounding permitted burns for different fire types as predictors (x_i):

$$PM_{2.5} = b_0 + \sum_{i=1}^{4} b_i x_i$$

The models are allowed to include a linear term for each predictor—burn area for silvicultural, land clearing, and agricultural fires and pile volume for pile fires. In the stepwise algorithm, a combination of forward and backward selection is used to systematically determine the terms in the final model using the p value for a chi-squared test of the change in the deviance after adding or removing a term as a criterion (a $p \leq 0.05$ threshold is defined to add terms to the model). To assess the explanatory power of a model, we use the adjusted coefficient of multiple determination ($\overline{R}^2$), which increases with the addition of a predictor only if the proportion of variation explained extends beyond the increase expected by chance. We compare the relative importance of each burn type on pollutant concentrations by applying the average increment method (Tonidandel & LeBreton, 2011). The method follows the principle of dominance analysis (Azen & Budescu, 2003) to determine the proportional contribution of each variable to the variation explained directly and in combination with other predictors in the model. When assessing the influence of meteorology on $PM_{2.5}$, we include daily mean temperature, precipitation, relative humidity, wind speed, and wind direction components (north-south and east-west), as well as first-order interactions between these meteorological variables, as potential predictors (y_i) in the multiple regression:

$$PM_{2.5} = b_0 + \sum_{i=1}^{4} b_i x_i + \sum_{i=1}^{6} b_{i+4} y_i + \sum_{i=1}^{5} \sum_{j=i+1}^{6} b_{ij} y_i y_j$$

3. Results and Discussion

From 2013 to 2016, the GFC issued permits for nearly 80,000 prescribed burns covering 1.5 million acres on average each year. During the same period, the FFS annually authorized permits for approximately 25,000 burns covering 2.5 million acres and 60,000 piles. Figure 1a shows all prescribed burns authorized by the GFC and FFS in 2016. Silvicultural fires accounted for 83% of the burn area in Georgia, with agricultural and land clearing fires representing 11% and 6%, respectively. In Florida, 63% of the burn area was characterized as silvicultural, while 36% was recorded as agricultural and 1% as land clearing. Excluding pile burns, the average size of these fires was approximately 100 acres. The largest amounts of prescribed burning were recorded in Southwest Georgia, Northwest Florida, and Southcentral Florida (Figure 1a). Close to 80% of the fires in Georgia were authorized between January and April. The seasonality is shown for a Southwest Georgia location in Figure 1b. This pattern is less evident in Florida, where 63% of the permitted burns were authorized during the first 4 months of the year.

High $PM_{2.5}$ concentrations were often observed within fire-intensive areas. For example, at Albany, Georgia, the average burn-season 24-hr $PM_{2.5}$ concentration from 2013 to 2016 was nearly 50% higher than the state average (Figure 1b), despite being a relatively small metropolitan area. During this period, nearly half of all moderate-to-high $PM_{2.5}$ observations (>15 μg m^{-3}) recorded from January to April by Georgia and Florida monitors occurred when a large burn area (>1,000 acres) was permitted within 60 km of the site on the day of the observation or the previous day (Figure 1c). Higher $PM_{2.5}$ levels in the region tend to coincide with heavier burning; over 80% of burn-season 24-hr $PM_{2.5}$ concentrations between 25 and 35 μg m^{-3} were recorded when more than 1,000 acres of burn area were permitted nearby. For concentrations exceeding the 24-hr National Ambient Air Quality Standard (35 μg m^{-3}), this fraction increases to 90%, with 43% of the observations coinciding with a very large amount of burning (>5,000 acres) close to the site.

Figure 2a shows the bivariate correlation between burn-season $PM_{2.5}$ concentration and nearby total permitted burn area (silvicultural, land clearing, and agricultural) at observational sites considered. In Georgia, all sites show a statistically significant ($p \leq 0.05$) positive correlation (mean PCC = 0.39) with a regression coefficient of 2.2 ± 0.5 μg m^{-3} per 1,000 permitted acres at 95% confidence. Permitted burn area explains over 20% of the variability in burn-season $PM_{2.5}$ concentrations at over a third of the state's monitors, most located in Georgia's Upper Coastal Plain (Figure 2b). At Albany, permitted burn area alone predicts close to 50% of the variation in observed concentrations. In comparison, associations between observed $PM_{2.5}$ concentrations and permitted burn areas in Florida are weaker (mean PCC = 0.19). While

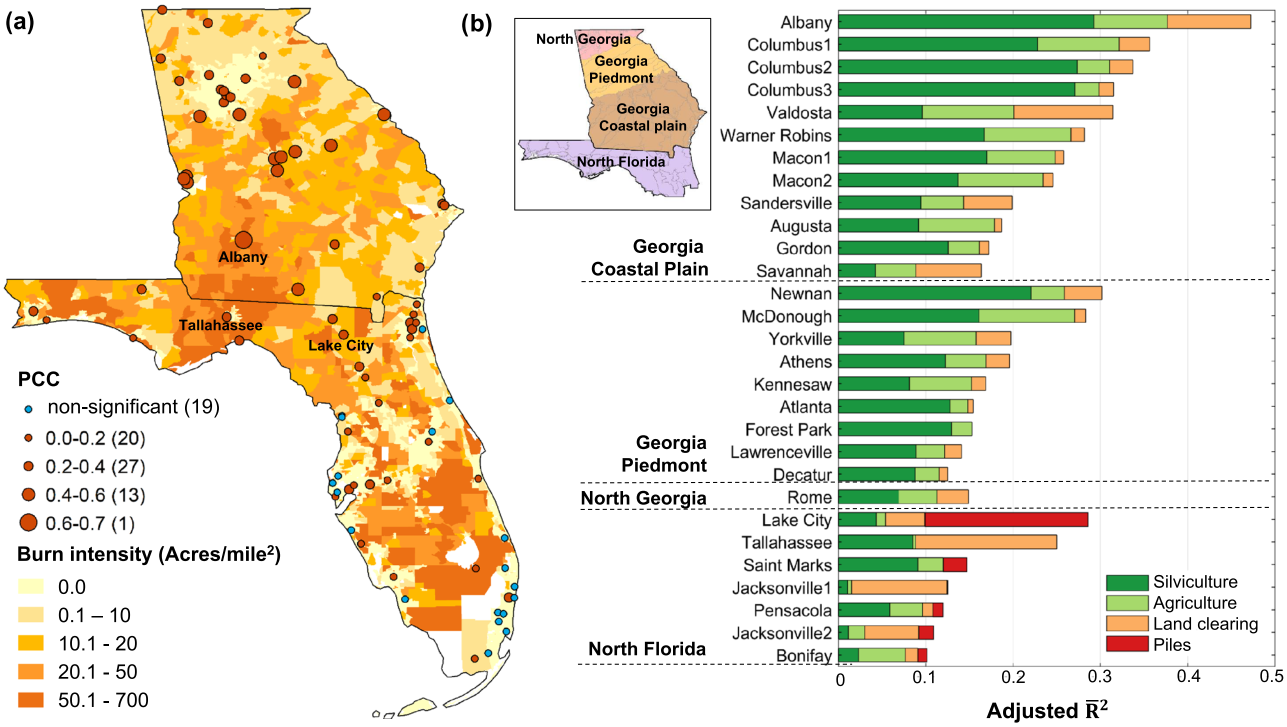

Figure 2. Influence of prescribed fire on $PM_{2.5}$. (a) Bivariate correlation between 24-hr $PM_{2.5}$ concentration and permitted burn area within 60 km of site on day of the observation and previous day for 2013–2016 burning seasons. Census-tract burn intensity is also shown. (b) Variability in 24-hr $PM_{2.5}$ concentrations (2013–2016) explained by multiple linear regression based on different types of burns. Geographic region and contribution of each burn type to $\bar{R}^2$ are shown for sites with highest explained variability. Permits considered are those within 60 km of site on day of the observation and previous day.

60% of the monitoring sites reflected a statistically significant correlation with burn area (0.6 ± 0.15 μg m^{-3} per 1,000 permitted acres at 95% confidence), burn area explains over 10% of the variability in concentrations at only three locations, all in North Florida. The seasonality in associations between $PM_{2.5}$ and burn area is also stronger in Georgia; burn-season correlations across Georgia are on average twice as large as those estimated for the complete year, while the ratio is close to 1.4 for Florida sites (Figure S2). These associations remain consistent across multiple years in Georgia but show greater interannual variability at Florida sites (Figure S3).

Accounting for burn type can increase the explanatory power of a generalized linear model of observed $PM_{2.5}$. Across Georgia, multiple regression using burn types as predictors can explain more than 20% of the variability in burn-season $PM_{2.5}$ at over 40% of sites. In Florida, the impact is evident at several northern locations, especially when adding pile fires as a variable. For example, at Tallahassee and Lake City, multiple regression can explain over 25% of the variation in $PM_{2.5}$ during the burning season. Figure 2b compares the influence of different burn types included as predictors at the sites with the largest explained variability. Silvicultural burn area is the dominant predictor at most Georgia sites, contributing approximately 60% of the $\bar{R}^2$ on average. However, the weight of agricultural and land clearing burns is also significant at some Georgia locations. In Northern Florida, the dominant burn type varies across sites. At Lake City, pile burns contribute the most to $\bar{R}^2$, while at Tallahassee, land clearing area carries the largest weight.

Figure 3 shows the burn-season bivariate correlation between $PM_{2.5}$ and surrounding permitted burn area recorded during varying periods of time. The influence of prescribed fire activity on observed air pollution persists for 1 to 2 days. The correlation is strongest when considering the total burn area on the day of the observation made at the monitor and the previous day. Beyond 1 day prior to the $PM_{2.5}$ observation, the number of monitoring sites with a statistically significant association and strength of the correlations drop

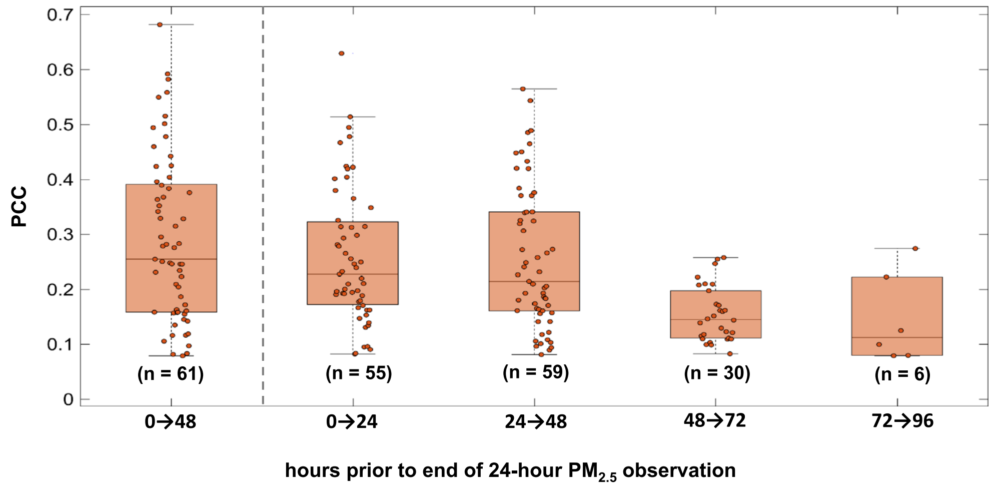

Figure 3. Duration of prescribed fire impacts on local $PM_{2.5}$. Boxes include significant correlations ($p \leq 0.05$) between burn-season 24-hr $PM_{2.5}$ concentrations and permitted burn area (within 60 km) across all Georgia and Florida sites considered based on varying burning periods, from the day of the $PM_{2.5}$ observation to 3 days prior. For each box, n is the total number of sites with a significant association, and dots show individual site correlations (2013–2016).

considerably. In Georgia, for example, while total permitted burn area on the day of the observation and previous day explain over 20% of the variability in 24-hr $PM_{2.5}$ concentrations at 35% of the state's monitors, the burn area permitted a day earlier does not match this level of explained variation at any site.

To explore how the influence of prescribed burning on pollution varies with distance, correlations between $PM_{2.5}$ concentration and burn activity were evaluated at increasing distances from the monitoring sites, ranging from 10 to 60 km. The spatial scale of the association varies across locations. At most sites, however, a radius over 60 km exceeds the coastal or state boundaries to which the permit data was confined, making it difficult to determine a consistent area influence of prescribed burning around the monitors. Still, at many sites, the correlation between $PM_{2.5}$ concentrations and surrounding permitted prescribed fire activity extends to 60 km away from the monitor during the burn season.

The association between fire activity and $PM_{2.5}$ pollution is stronger for permit-based burn areas than burn areas derived from satellite detections. Figure 4a compares the magnitude of bivariate correlations between $PM_{2.5}$ concentrations and the two sources of fire data over the 2015 and 2016 burn seasons. With few exceptions, the association is stronger when correlating $PM_{2.5}$ with permitted burn area (>85% of sites). Across statistically significant sites, the mean PCC based on permitted area is 55% higher than that based on satellite-derived burn area. Over Georgia, permitted burn area explains over 20% of the variability in observed $PM_{2.5}$ at over a third of the state's monitoring stations, while this is true for satellite-derived area at only one site.

To further place the association between $PM_{2.5}$ and surrounding prescribed fire into context, it is compared to the influence of important meteorological drivers of air quality (temperature, precipitation, relative humidity, wind speed, and wind direction). Across sites, temperature, wind direction, and interactions between relative humidity and wind variables are the terms most frequently included as significant predictors in the generalized linear models of $PM_{2.5}$. Figure 4b compares the relative weights of permitted burning and weather data as predictors of $PM_{2.5}$ in a generalized linear model. At most locations (>60%), the explanatory power of nearby permitted fire is greater than that of the meteorological predictors, suggesting that prescribed fire has stronger influence on $PM_{2.5}$. This is particularly true at Georgia sites, where the average variability in 24-hr $PM_{2.5}$ concentrations explained by burning is over 4 times larger than that explained by the meteorological variables. In contrast, at most monitoring sites near the coast or large metropolitan areas, including most Florida locations, the weight of fire-related explanatory variables relative to meteorology is substantially lower.

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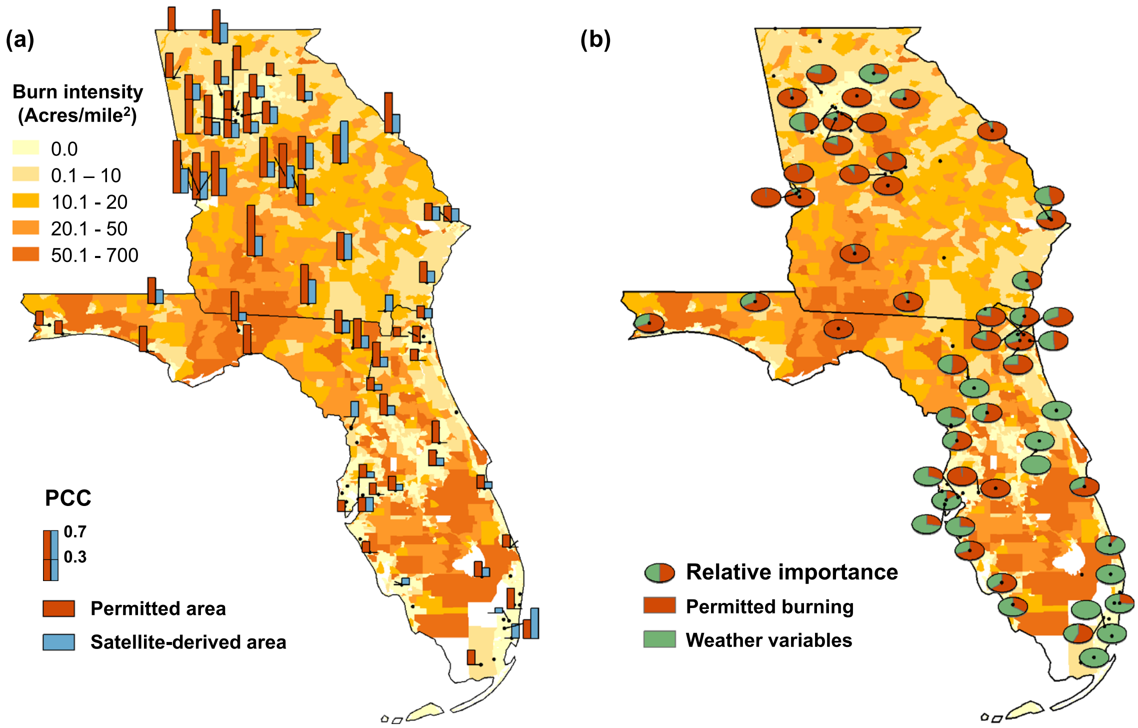

Figure 4. Associations between $PM_{2.5}$ and burning permits, satellite-detected fires, and meteorology. (a) Significant ($p \leq 0.05$) bivariate correlations between 24-hr $PM_{2.5}$ concentration and permitted or satellite-derived burn area (2015–2016 burning seasons). (b) Relative importance of permitted burning and meteorological predictors in explaining 24-hr $PM_{2.5}$ concentration variability based on multiple regression ($p \leq 0.05$) at sites with concurrent $PM_{2.5}$ and weather data (2013–2016 burning seasons). Permits and satellite-derived burns are within 60 km of site on day of the $PM_{2.5}$ observation and previous day. Meteorology is daily average on day of observation. Census-tract burn intensity is also shown.

4. Conclusions

The analyses of burn permit records and observed air quality included in this study reveal a significant association between prescribed fire and $PM_{2.5}$ pollution at multiple Southeastern locations during the early months of the year. It is notable that a prescribed fire signal in monitored air quality was identified at these sites based on burn permit data, given that the fire records include uncertain geo-coordinates and no verification of burns, postburn information, or fuel characteristics. Still, as much as 50% of the variability in observed $PM_{2.5}$ during the burn season can be explained by nearby burn permits alone, despite the noise imposed by weather and the effects of other emissions sources. It is similarly noteworthy that at many of the locations considered, the correlation between $PM_{2.5}$ and permitted burning is stronger than between $PM_{2.5}$ and important meteorological drivers of air quality. Results also suggest that the influence of prescribed burning on $PM_{2.5}$ can persist for 1 to 2 days. These associations can remain consistent across multiple years but differ throughout the study domain. Silvicultural fires have the largest impact at most sites, but land clearing, agricultural, or pile burns dominate at specific locations. The linkages between prescribed burning permits and monitored $PM_{2.5}$ are generally stronger in Georgia than in Florida. Weaker associations at Florida sites may be related to less concentration of fire into a defined burning season, greater inter-annual variability in burning, a larger impact of meteorology on pollutant concentrations, and closer proximity to the coast and large urban areas at most monitoring sites. However, it is likely that the strong connections between prescribed fire and air quality observed over Georgia are representative of other Southern states, often further inland, more rural, and with active burning programs, albeit incomplete fire records. Additional prescribed fire data are required to adequately assess the relationship across the region.

Our results highlight several needs to improve characterizations of prescribed burning impacts on air quality in the Southeastern United States. In agreement with previous studies (Huang et al., 2018; Nowell et al., 2018), we find that smaller fires typical of prescribed burning are likely to go undetected by remote sensing products, making satellite-based detections highly uncertain. This underlines the need for ground-based fire data in assessments of air quality impacts over the region. While this study focuses on states with some of the most complete burn permits records, permit data vary widely across agencies. Digital records in other states, if available, are often incomplete and include less detailed data fields. Capturing additional information, including improved geographic locations, burn start times and durations, fuel characteristics, and atmospheric conditions would enhance the value of bottom-up fire records for air quality analyses. In particular, postburn confirmation of fire occurrence and area treated would be beneficial, as existing permit systems do not monitor if permitted burns were actually conducted or their true size. This study shows that considering pile burns, unaccounted for in prior studies, can be important. Our results also point to a need for increased air quality monitoring and emissions measurements within burn-intensive regions, in agreement with the smoke modeling community (Liu et al., 2019). Some of the most intense burning and strongest associations between fire and air pollution occur in areas where monitors are scarce, such as Southwest Georgia and Southcentral Florida.

Addressing these research gaps would aid efforts to produce a complete assessment of prescribed fire's role in the region's air quality. While prescribed fire is recognized as the largest source of $PM_{2.5}$ emissions in the Southeast, existing emissions inventories and observational networks likely do not capture its full magnitude. Thus, estimates of prescribed burning impacts on regional air quality and public health based on current fire data are subject to large uncertainties. As the use of prescribed fire continues to gain popularity and extend to additional areas, while emissions from other major sources decrease, its importance in U.S. air quality will grow. However, prescribed burning is substantially different from the emission sources traditionally targeted by air pollution reduction efforts. Prescribed fire can reduce the risk of uncontrolled wildfires with potentially higher emissions, in addition to other land management benefits. Adequate strategies that consider these complexities must be developed to mitigate its impacts. Better characterizing its effects on air pollution is an essential step toward this goal.

Data Availability Statement

The data used for this study are available at https://fgarciam.wordpress.ncsu.edu/data.

Acknowledgments

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